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Design and Simulation of a new Concrete Storage Unit

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Abstract

Solar Thermal Electricity (STE) is an important alternative to PV electricity production, due to the cost competitiveness in locations with high DNI as well as for the intrinsic value of having thermal storage which can give an important contribution to the energy mix in countries like Spain where STE has more than 2500MW installed capacity. In recent years, research has been performed, on alternative storage systems, to which features like modularity and validation of new thermal storage materials are important with the goal of achieving lower investment cost. Concrete storage has been studied in the past up to an operating temperature of 500ºC [1] [2], and several prototypes were built and tested without reaching commercial plants. Nowadays, new design and new concrete mixes are under research in order to validate its usage up to 550ºC [3]. Simulation results leading to this new design are presented.

Keywords: *Energy Storage, High Temperature, Concrete mix, Solid material*

1. Introduction

Decreasing the cost of an overall CSP plant is a fundamental goal in order to make this technology more cost competitive. Current commercial solutions include, a 2-tank molten salt indirect system (e.g. Andasol plant in Spain, 7.5h of storage capacity), a 2-tank molten salt direct system (e.g. Gemasolar plant in Spain, 15h of storage capacity) or steam accumulators (e.g. Khi plant in South Africa, 2h storage capacity). Alternative storage systems with concrete have been analyzed in the projects WANDA, ITES and WESPE (Fig.1), with thermal cycles performed between 315ºC and 390ºC and a thermal capacity of 350kWh. A specific heat capacity of 916 J/kgK [2] was measured for temperatures in the range 300-390°C. However, the concrete module design was optimized for a full scale 1010MWh storage for Andasol type CSP plants.

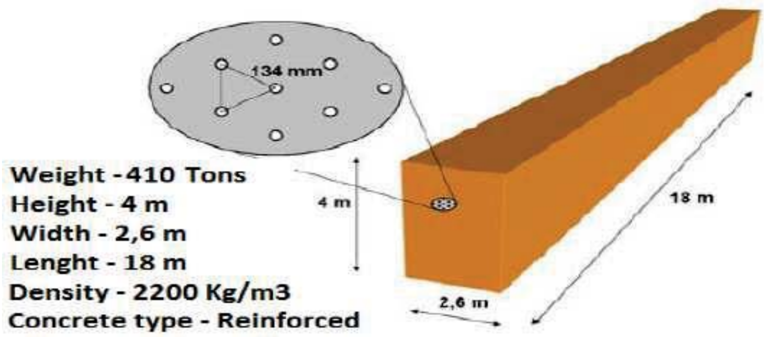

Fig. 1: Concrete Module designed in Project WANDA

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2. Methodology

In order to obtain a model that could be evaluated against previous work, a module with similar outer dimensions was used as a starting point, a cross section of the storage module is shown in Fig. 2. The tube register consists of 609 stainless steel tubes with an outer diameter of 18 mm. The tubes embedded in the storage module were arranged in a triangular pitch to obtain a better temperature distribution in the solid storage module. The entire storage consists in several storage units with regular hexagonal cross sections.

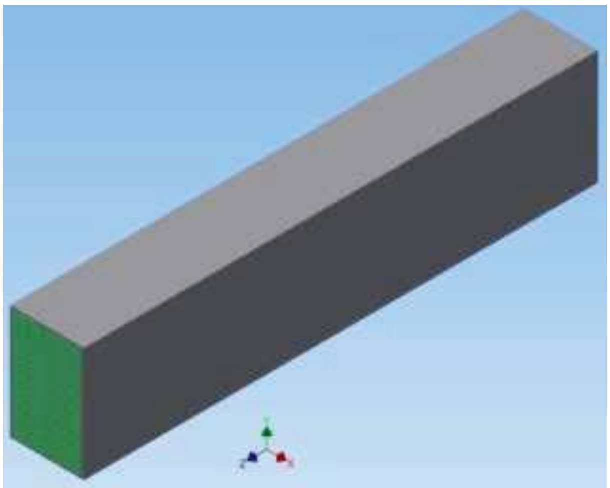

Fig. 2: Concrete Module with dimensions 2,6*18*4m [W*L*H]

The analysis of the storage unit was then simplified by substituting cylindrical storage unit geometry for the regular hexagonal shapes (Fig.3) with the same cross sectional area. The geometries were related by:

– (eq. 1)

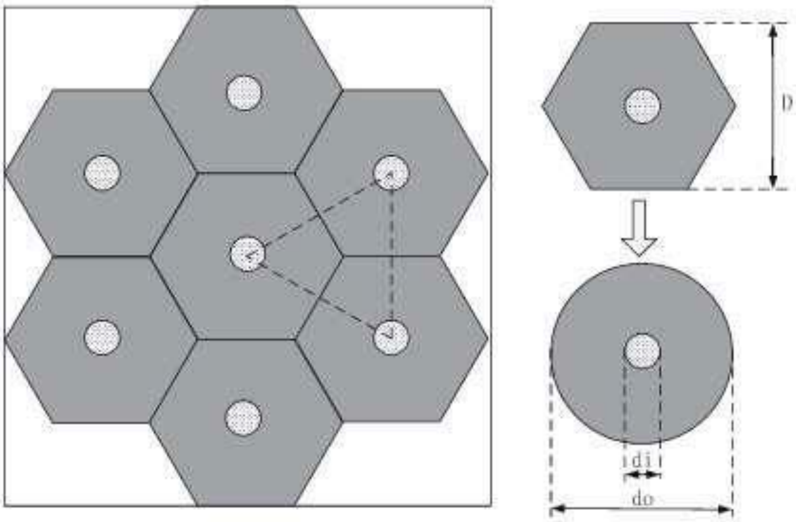

Fig. 3: Cross section of the solid storage module

The model is based on the following assumptions:

- the storage module has the same thermal behavior as the cylindrical storage unit shown in Fig. 4;
- thermal conduction in the axial direction in the fluid is negligible;
- the HTF directly contacts the solid;
- tube thickness can be assumed to be zero;
- there are no heat losses from the storage unit to the surroundings;

The finite element method is applicable to the thermal conduction in the solid media in the radial direction; thus:

(eq. 2)

The 3D model can be simplified to a 2D mesh of nodes.

Assuming that the mass flow rate, , is constant over the length of the tube, the thermal energy balance for the fluid in the differential control volume, *dz*, in Fig. 4 is:

(eq. 3)

Where:

is the effective heat transfer coefficient in the tube;

P is the heat transfer surface perimeter

is the cross section of the tube

Substituting the average fluid velocity in the cylindrical heat storage unit , and rearranging Eq.(3), the fluid energy balance equation becomes:

(eq. 4)

For the solid storage material, a mesh of nodes was used in the same control volume *dz* as shown in Figs. 4 and 5. The same *dz* was used for the spacing in the nodes in the radial direction.

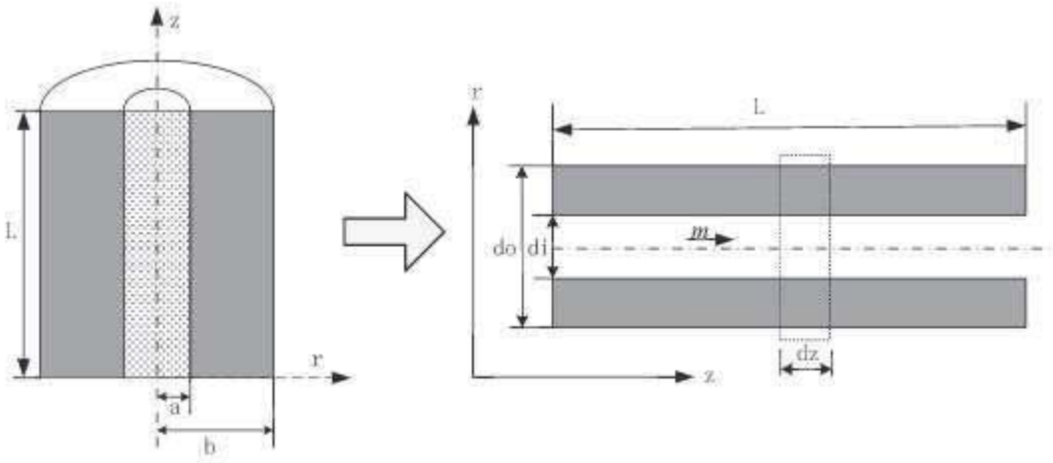

Fig. 4: Cylindrical heat storage unit model

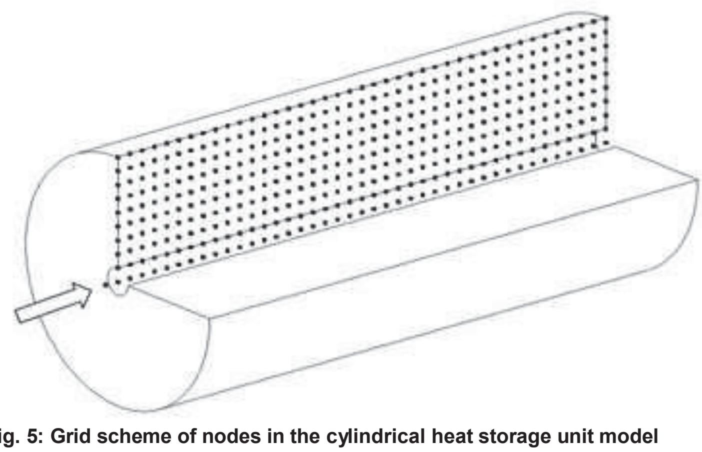

Fig. 5: Grid scheme of nodes in the cylindrical heat storage unit model

For the two-dimensional system of fig. 5, under transient conditions with constant properties and no internal heat generation, the appropriate form for the heat equation is:

—— —— —— (eq. 5)

Concrete was used as the storage material and *Solar Salt* (a mixture of sodium and potassium nitrates) the Heat Transfer Fluid (HTF). The thermos-physical properties of the concrete mix considered are listed in table 1:

Tab. 1 - Thermal physical properties of concrete

Material	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)	Viscosity (Pa s)
Concrete (400 °C)	2250	1050	1.20	–

The temperature dependent equations used to obtain the thermo-physical properties of the fluid are listed below. Since the changes in the overall heat transfer coefficient are so low when we change the thermo-physical properties with temperature, a fixed temperature of 823 K was assumed in the calculation of the properties. The conductivity is not temperature dependent and it is assumed to be 0.45.

- For density: (eq. 6)
- For viscosity:

(eq. 7)

- For heat capacity: (eq. 8)

3. Results and Discussion

A Matlab simulation was performed using the methodology and equations described. To simulate real conditions of a solar power plant, an 8 hour charging cycle was assumed. Constant concrete properties during the cycle were considered. It is assumed that the fluid leaves the collector field at 550 ºC and enters the solid storage at that same temperature.

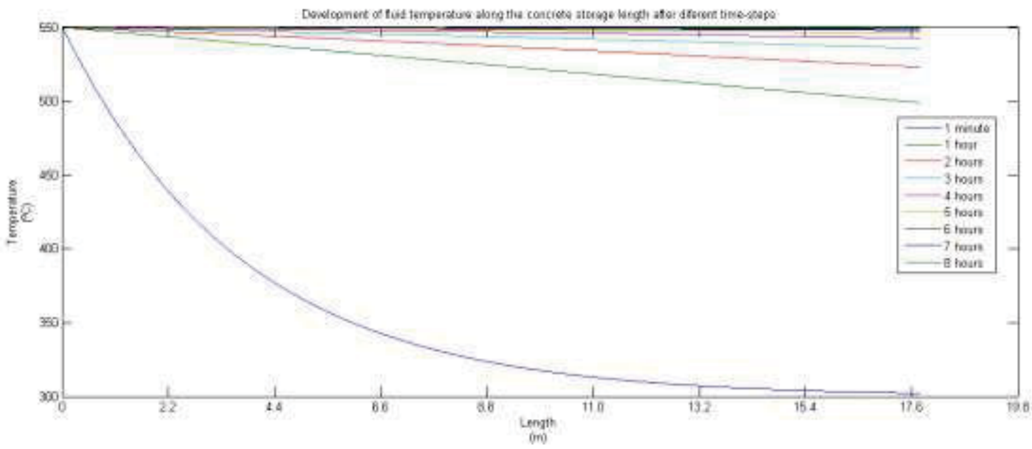

Fig. 6 - Development of fluid temperature along the concrete length with 1 hour intervals

In fig.6 it is represented the development of fluid temperature (solar salt) over the length of the module after different time steps varying from 1min up to 8hours.

In fig.7 it is represented the development of concrete temperature for radial nodes in an 8 hour charging cycle in the entrance and exit region of the module.

In fig.8 it is represented the development of temperature for different radial layers in the concrete over the module length. In these cases the considered was 250 ºC (initial temperature of 300ºC and final temperature of 550ºC for the concrete), the concrete thermal conductivity and the flow rate corresponding to the velocity of in the cross section of a single tube.

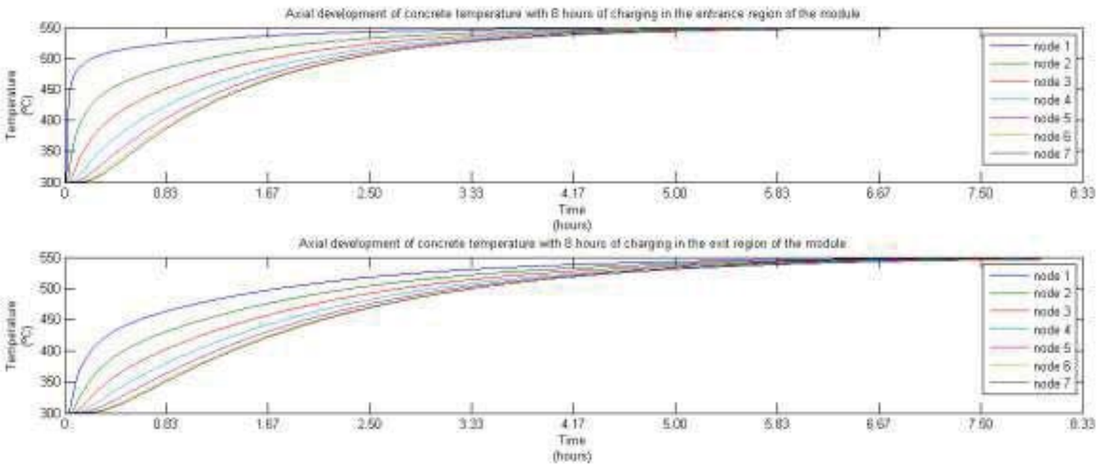

Fig. 7 – Development of concrete temperature in a 8 hour cycle in the entrance and exit region of the cylindrical module from node 1 (after fluid) to node 8 (concrete border)

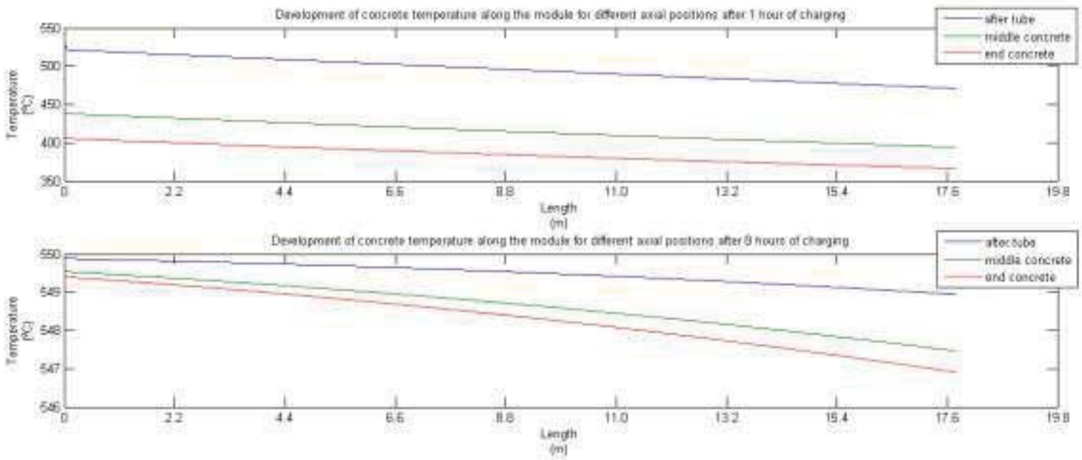

Fig. 8 - Development of concrete temperature along the length for different radial positions after 1h, 8h time steps

As it's shown in Fig. 6 the initial fluid temperature drop is very high, due to the high between the fluid inlet temperature and the concrete. This tends to change over time as the module reaches thermal balance.

In Fig. 7 is visible the radial development of temperature over time. In the entrance region the rise in temperature is faster than in the exit region as it is expected, especially the node nearest to the tube. After 5 hours one can observe that the module is fully charged, as the temperature in all the nodes reaches steady-state.

Finally in Fig. 8 it is visibly that temperature slightly drops along the concrete module length in every case as it is expected, with the nodes after the tube being always the ones with higher temperatures.

Knowing that concrete mix development is one of the current research topics, where interesting results have been obtained by several researchers, it was simulated an increase in the concrete thermal conductivity in order to evaluate changes in heat transfer and temperature development in the concrete storage unit.

The parameter thermal conductivity was simulated to have an enhancement to , behavior along the time, up to 8h is shown in the following figures.

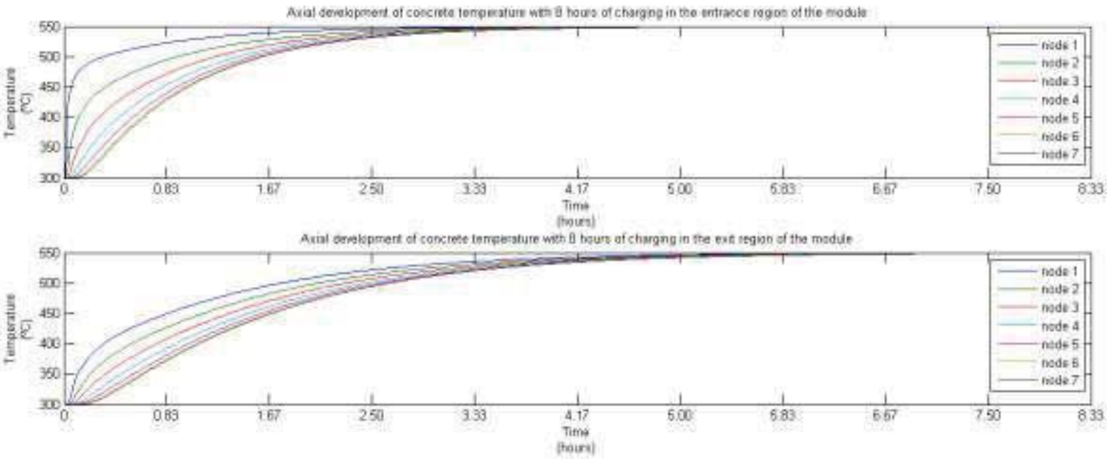

Fig. 9 - Development of concrete temperature in a 8 hour cycle in the entrance and exit region of the cylindrical module from node 1 (after fluid) to node 8 (concrete border), for radial development.

The main difference is observed in the radial development, where the development of temperature in different radial nodes is much more similar, seen in the less spaced curves of the different nodes.

In Fig.9 an increase in charging behavior can be observed when compared with Fig.7, that is, instead of 5h for full charge it takes less than 4h. However, in order to achieve further improvement in overall heat transfer, not only the material properties are important, but also the design needs to be optimized. For that reason, following the results obtained, a new design is proposed as shown in Fig.10 and Fig.11.

This new design section considers a new concrete mix developed with a thermal conductivity of about 2 W/m*K. The number of pipping is reduced significantly (when compared with steam as a HTF) since the heat transfer fluid are molten salts and not steam, meaning that the thickness of the pipes can be reduced, and heat exchange between fluid and concrete improved by means of fins welded to the pipping.

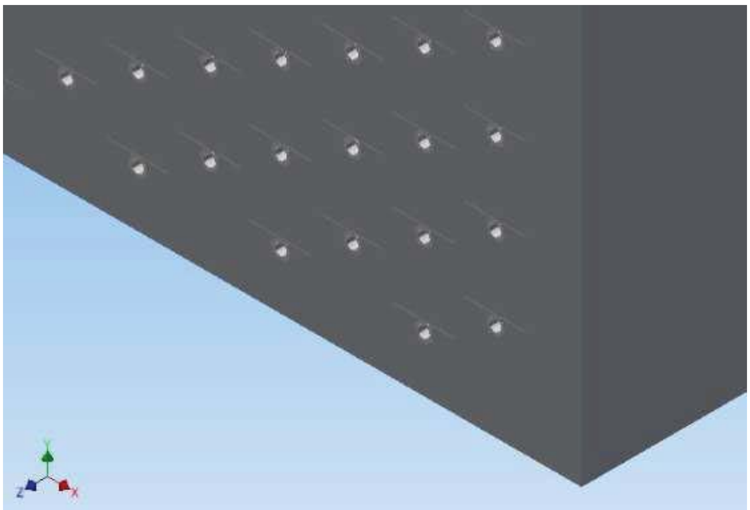

Fig. 10: Concrete Module new section design, isometric perspective

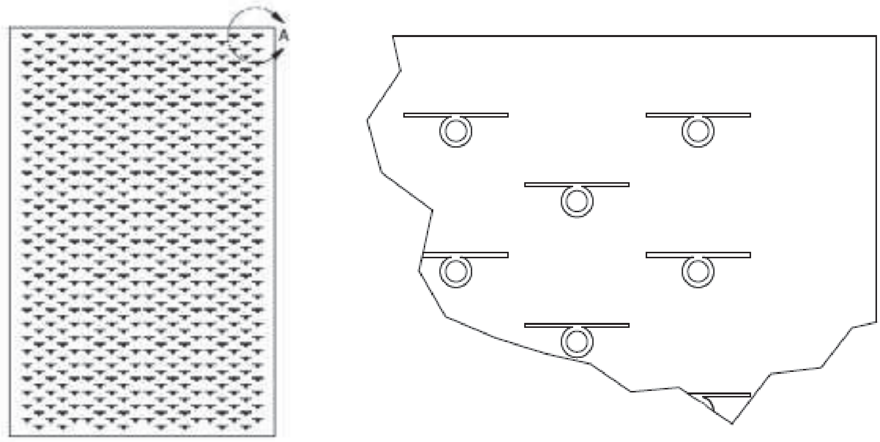

Fig. 11: Concrete Module new section design, (left side: section, right side: detail)

4. Conclusions

Simulation using Matlab is an appropriate tool for simulating thermal behavior of a concrete heat storage unit. Different cases have been simulated to demonstrate the methodology and the impact of improving some of its features. Enhancing properties like thermal conductivity is possible to be evaluated through the method applied. The improvement in the thermal conductivity of concrete allows a faster increase in temperature in the concrete as well as less difference in the temperature along the radial nodes, showing that the heat transfer inside the concrete is faster between the nodes.

Using the same method other parameters (like the flow rate) can be varied in order to simulate its behavior. Nevertheless, in order to increase significantly the charging and discharging performance, new section designs need to be fully evaluated and simulated. A new design has been proposed to improve the overall concrete storage unit behavior.

A concrete module is a concept that has several advantages: can be planned with a certain number of units, easily scalable, can be built in phases, the investment can be diluted for a longer period of time, can operate partly depending on the radiation among other advantages. If all technological aspects are taken into consideration, a significate improvement can be achieved, making concrete storage an interesting alternative to mainstream molten salts tank storage.

5. References

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